Protection Switching for Optical Bursts Using Segmentation and Deflection Routing

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***Abstract*— Burst segmentation in OBS networks can significantly reduce the amount of data that is lost due to contention events by dropping or deflecting only the portion of a burst that overlaps another contending burst. In this letter, we demonstrate how segmentation combined with deflection routing can be used to reduce the amount of data that is lost when network elements fail. By enabling an OBS switch to deflect the tail-end segments of bursts that are in transmission as soon as it becomes aware of a downstream link failure, the retransmission of lost data can be reduced.**

***Index Terms*— optical burst switching, protection and restoration, deflection routing, burst segmentation**

I. Introduction

Optical burst switching (OBS) used out-of-band (OOB) control packets traveling in advance of bursts of data to reserve resources at optical switches, so that the data burst sees a dedicated lightpath between its entry and exit points in the network [1]. Since the introduction of the concept, a considerable amount of work has led to numerous refinements of the basic OBS architecture. One such enhancement, burst segmentation, reduces burst loss rates by allowing OBS switches to drop portions of bursts, rather than entire bursts, when there is competition for switching resources [2]. Another contention resolution technique, deflection routing, allows bursts to be forwarded on alternate output ports if the preferred output port is busy [3]. Combining segmentation and deflection routing has been shown to improve OBS network performance [4].

Deflection routing can be used for failure recovery by sending bursts on alternate paths to their intended destinations. As soon as a failure is detected, the OBS switch immediately upstream from the failure sends bursts that are destined for the affected output port to other output ports The congestion caused by displaced traffic can be reduced by deflecting traffic destined to cross the failed link at switches that are more than one hop upstream from the failure [5]. If burst segmentation is being used as a contention resolution mechanism in an OBS network that also supports deflection routing, these two techniques can be used to reduce data losses due to failures. This letter presents an analytical model that allows us to quantify the amount of data that can be salvaged using this approach.

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II. Analysis

We use a two-state Markov system, depicted in Fig. 1, to model the sequence of bursts on the outgoing port of an OBS switch. The transition rates out of the `burst` and `gap` states are β and γ, respectively. The model is a special case of the three-state system developed in [6] to study a burst stream that comprises short and long bursts. Each burst is divided into N segments whose length, $1/\sigma$, is deterministic. The number of segments in each burst can be deterministic or random; we consider both cases in this letter. The length of a given burst is $B = N/\sigma$; when N is random, B has density f_B and mean $1/\beta$. G is the length of the gap between bursts; we assume that it is exponentially distributed with mean $1/\gamma$. We define the burst/silence cycle $C = B+G$ to be the sum of the duration of a burst and the duration of the gap immediately following it, as shown in Fig. 2(a). The expected value of C is $\beta^{-1} + \gamma^{-1}$.

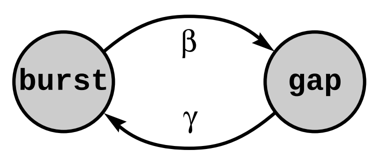

Fig. 1. Two-state Marcovian model of the traffic on an OBS switch output port. β and γ are the transition rates out of the `burst` and `gap` states, respectively.

We assume that failure events are characterized by a Poisson arrival process and that the time required for the switch to detect each failure is deterministic. Thus, the failure detection events at an OBS switch follow a Poisson process that is a time-shifted copy of the failure arrival process. We are interested in the burst/gap cycle in which the failure detection time falls. Let $t = 0$ correspond to the leading edge of the burst in this cycle. We assume that the average time between failures is much larger than the average burst/gap cycle duration, so that the probability of more than one failure in a given cycle is negligible.

Let t_N be the failure notification time, i.e. the time at which the switch is notified by its downstream neighbor that a link failure has occurred. Because failure events and failure notification events occur according to a Poisson process, and because we are conditioning on the occurrence of a notification event in the burst/gap interval $[0, C]$, it follows that the notification time t_N is uniformly distributed over the interval $[0, c]$, given a particular value c for C. Thus, given a value

n for N (which also determines the conditional length of the burst, b), and a value g for G, the length of the gap between bursts, the conditional density for t_N is

$$f_{t_N|n,g}(t) = \begin{cases} 1/(g+n/\sigma), & 0 \le t < c \\ 0, & \text{else.} \end{cases} \tag{1}$$

Let X be the amount of data that can be salvaged when burst segmentation is used. In order to determine μ_X, the average value of X, we compute the expected duration of the time interval $[t_N, B]$. Segments whose transmission time falls after the failure notification time are deflected to other output ports. Performing this operation requires creating a new header for the deflected group of segments and optically buffering them in a fiber delay line to create a sufficiently large time interval between the new header and the deflected segments. Without burst segmentation, this block of data will be lost along with the rest of the burst. If the failure notification time occurs after the tail end of the burst, i.e. if $t_N > B$, the entire burst will be lost regardless of whether segmentation is used.

If t_N occurs in the kth segment (i.e., in the time interval $[(k-1)/\sigma, k/\sigma])$, that segment cannot be recovered because its header was already transmitted over the failed output port. The segments that follow the kth segment can be deflected onto an alternate output port. Using Fig. 2(b), we find that the amount of data that can be salvaged is

$$X(N;t_N) = \begin{cases} \frac{N-k}{\sigma}, & \frac{k-1}{\sigma} \le t_N < \frac{k}{\sigma}, \\ & k = 1,2,\ldots,N \\ 0, & t_N \ge N/\sigma. \end{cases} \tag{2}$$

Using Eq. (1) and Eq. (2), we can compute $\mu_{X|n,g}$, the expected amount of salvageable data conditioned on values for N and G:

$$\begin{aligned} \mu_{X|n,g} &= \int_0^\infty X(n;t) f_{t_N|n,g}(t)\, dt \\ &= \frac{1}{g+n/\sigma} \sum_{k=1}^{n} \int_{\frac{k-1}{\sigma}}^{\frac{k}{\sigma}} \frac{n-k}{\sigma}\, dt \\ &= \frac{1}{g+n/\sigma} \frac{n(n-1)}{2\sigma^2} = \frac{b(b-1/\sigma)}{2(b+g)}. \end{aligned} \tag{3}$$

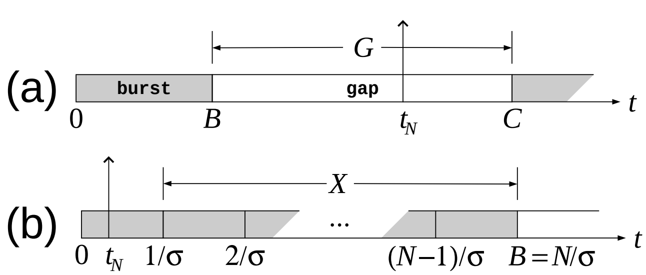

Fig. 2. (a) The structure of a burst/gap cycle. The failure notification time t_N is uniformly distributed over the cycle time. When failure notification takes place during the gap, no tail-end salvaging as possible. (b) The effect of segmentation on the amount of recoverable data. The segments that follow the segment containing t_N can be deflected to alternate output ports, so X is the amount of salvagable data.

To obtain μ_X, we use $\mu_{X|n,g}$ from Eq. (3) and $f_{N,G}(n,g) = f_G(g) \Pr\{N=n\}$, the joint density of N and G, which are independent:

$$\mu_X = \int_0^\infty f_G(g) \left(\sum_{n=1}^{\infty} \Pr\{N=n\} \mu_{X|n,g} \right) dg. \tag{4}$$

We consider two burst size distributions. In the first case, the burst length is deterministic. Consequently, the number of segments per burst, N, is also deterministic with value σ/β, where σ/β is an integer, and its mass function is $\delta(n-\sigma/\beta)$, where $\delta(n)$ is the Kronecker delta function. Since G is exponentially distributed, Eq. (4) becomes

$$\mu_X = \int_0^\infty \frac{\gamma e^{-\gamma g}(1-\beta/\sigma)}{2\beta^2(g+1/\beta)}\, dg = \frac{\gamma e^{\gamma/\beta}}{2\beta^2}(1-\beta/\sigma)\Gamma(0,\gamma/\beta), \tag{5}$$

where $\Gamma(a,x) = \int_x^\infty u^{a-1}e^{-u}\, du$ is the incomplete gamma function. As the segment length decreases while the average burst size $1/\beta$ remains fixed (i.e., as $\sigma \to \infty$), the conditional expected amount of salvageable data given by Eq. (3) approaches $b^2/[2(b+g)]$, and μ_X from Eq. (5) approaches

$$\lim_{\sigma\to\infty} \mu_X = \frac{\gamma e^{\gamma/\beta}}{2\beta^2} \Gamma(0,\gamma/\beta). \tag{6}$$

If the number of segments in the burst is geometrically distributed, with probability mass function

$$\Pr\{N=n\} = \Pr\{B=n/\sigma\} = (1-p)p^{n-1}, \quad n=1,2,\ldots$$

applying Eq. (4) yields

$$\mu_X = \frac{\gamma(1-p)}{2\sigma^2} \sum_{n=1}^{\infty} n(n-1)p^{n-1} e^{\gamma n/\sigma} \Gamma(0,\gamma n/\sigma). \tag{7}$$

This does not produce a closed-form result but we can obtain one in the limit as the segment size becomes small. Because $\mu_B = 1/\beta$, it follows that $p = 1-\beta/\sigma$. We show that as the average segment length $1/\sigma$ decreases while the average burst size remains fixed, the density of B approaches an exponential density with mean $1/\beta$. Because $B = N/\sigma$, it follows that $\Pr\{B>t\} = \Pr\{N > \lfloor\sigma t\rfloor\} = (1-\beta/\sigma)^{\lfloor\sigma t\rfloor}$. Thus $\log(\Pr\{B>t\}) = \frac{\lfloor\sigma t\rfloor}{\sigma}\log((1-\beta/\sigma)^\sigma)$, and $\lim_{\sigma\to\infty}\log(\Pr\{B>t\}) = t\log\left(e^{-\beta}\right) = -\beta t$. Therefore $\lim_{\sigma\to\infty}\Pr\{B>t\} = e^{-\beta t}$ and the burst length is exponentially distributed in the limit. Recalling that $\lim_{\sigma\to\infty}\mu_{X|n,g} = b^2/[2(b+g)]$, we can get μ_X by computing

$$\mu_X = \int_0^\infty\int_0^\infty \frac{b^2}{2(b+g)} f_{B,G}(b,g)\, db\, dg, \tag{8}$$

where $f_{B,G}$ is the joint density of B and G. Since they are independent and exponentially distributed with respective means $1/\beta$ and $1/\gamma$, Eq. (8) becomes

$$\begin{aligned} \mu_X &= \frac{\beta\gamma}{2}\int_0^\infty e^{-\gamma g}\left(\int_0^\infty \frac{b^2}{(b+g)} e^{-\beta b} db\right) dg \\ &= \frac{\beta\gamma}{2}\left[\int_0^\infty \frac{1-\beta g}{\beta^2} e^{-\gamma g} dg \right. \\ &\quad \left. + \int_0^\infty g^2 e^{(\beta-\gamma)g}\left(\int_{\beta g}^\infty \frac{e^{-b}}{b} db\right) dg\right]. \end{aligned}$$

The first integral can be evaluated directly. The double integral can be simplified by changing the order of integration, which gives us

$$\begin{aligned}\mu_X &= \frac{\beta\gamma}{2}\left[\frac{\gamma-\beta}{\beta^2\gamma^2} + \int_0^\infty \left(\int_0^{b/\beta} g^2 e^{(\beta-\gamma)g} dg\right) \frac{e^{-b}}{b} db\right] \\ &= \frac{(\beta-\gamma)(\gamma-3\beta) - 2\beta^2 \log(\gamma/\beta)}{2\beta(\beta-\gamma)^3/\gamma}. \quad (9)\end{aligned}$$

Equation (9) assumes the indeterminate form $0/0$ when $\gamma = \beta$. Applying L'Hôpital's Rule yields $\lim_{\gamma\to\beta} \mu_X = \beta^{-1}/3$.

In Fig. 3, we plot the amount of data that can be salvaged from a failure event versus the output port load $\rho = \gamma/(\beta+\gamma)$, which is the probability that the output port is active. We express the amount of salvageable data as a fraction of the average burst length, which we obtain by multiplying μ_X by β. We plot results for both deterministic and geometrically distributed burst lengths where the number of segments per burst, $N = \sigma/\beta$, is 2 and 10 using Eq. (5) and Eq. (7), respectively. We also plot results for the case where $\sigma \to \infty$, using Eq. (6) and Eq. (9) for the deterministic and exponentially distributed cases. To generate the plots, we use a change of variables $w = \gamma/\beta = \rho/(1-\rho)$ so that, for example, Eq. (9) becomes

$$\beta\mu_X = \frac{w((1-w)(w-3) - 2\log(w))}{2(1-w)^3}. \quad (10)$$

To plot Eq. (7), we also use the fact that $p = 1 - \beta/\sigma$, giving

$$\beta\mu_X = \frac{w}{2N^3} \sum_{n=1}^{\infty} n(n-1)(1-N^{-1})^{n-1} e^{nw/N} \Gamma(0, nw/N). \quad (11)$$

If $\sigma = \beta$, the amount of salvageable data is 0 because it is not possible to redirect a partial segment to an alternate output port. For other values of σ, the average performance of the burst segmentation scheme is better when the burst length is geometrically distributed. The maximum increase in salvageable data with respect to the deterministic case is 0.0282 for $\sigma/\beta = 2$ and 0.0414 for $\sigma/\beta = 10$. As the output port becomes fully utilized (i.e., as $\rho \to 1$), $\beta\mu_X \to (1-\beta/\sigma)/2$, as shown in the figure. Because of this, it is apparent that if there are more than 10 segments in the average burst, we will achieve performance that is close to the theoretical maximum. Segmenting bursts at shorter time intervals increases both complexity and overhead. Network designers can use the models presented in this letter to determine how finely segmented the bursts can be while keeping system costs within acceptable limits. Finally, we note that in all cases, the best that we can do is to salvage $1/2$ of a burst on average.

III. Summary

In this letter, we developed a theoretical model that allows us to calculate the average amount of data that can be salvaged after a failure on a given output wavelength at an OBS switch. We used this model to compute the mean salvageable burst length when the duration of the gap between bursts is exponentially distributed and when the burst length is either fixed or exponentially distributed. The salvaging mechanism described in this letter provides an added benefit to OBS networks

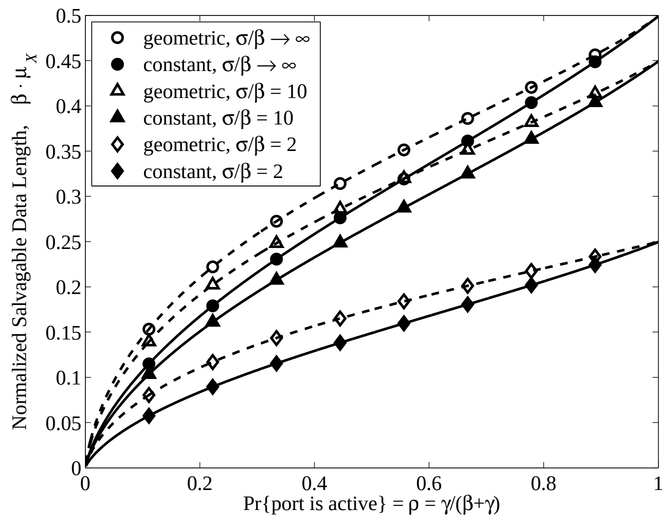

Fig. 3. Theoretical values of the burst fraction $\beta\mu_X$ that is salvageable after a failure event if burst segmentation and deflection routing are used.

that use burst segmentation and deflection routing to support contention resolution. Through salvaging, the segmentation architecture can be extended to support failure recovery at little additional cost to the network operator.

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